



Agronomic implications of waterfowl management in Mississippi ricefields

Scott W. Manley, Richard M. Kaminski, Kenneth J. Reinecke, and Patrick D. Gerard

Abstract Ricefields are important foraging habitat for waterfowl and other waterbirds in several North American wintering areas, including the Mississippi Alluvial Valley (MAV). Rice growers are likely to adopt management practices that provide habitat for waterfowl if agronomic benefits also occur. Therefore, we conducted a replicated field experiment during autumn through spring 1995–1997 to study effects of postharvest field treatment and winter-water management on agronomic variables including biomass of residual rice straw, cool-season grasses and forbs (i.e., winter weeds), and viability of red rice (*Oryza sativa* var.). The treatment combination of postharvest disking and flooding until early March reduced straw 68%, from 9,938 kg/ha after harvest to 3,209 kg/ha in spring. Treatment combinations that included flooding until early March were most effective in suppressing winter weeds and decreased their biomass in spring by 83% when compared to the average of other treatment combinations. Effects of treatment combinations on spring viability of red rice differed between winters, but no significant effects were found within winters. Autumn disking followed by flooding until early March reduced rice straw and suppressed winter weeds the most, but with additional costs. To obtain the most agronomic benefits, we recommend that rice growers forgo autumn disking and flood fields until early March, which will provide moderate straw reduction, good weed suppression, and predicted savings of \$22.24–62.93/ha (U.S.) (\$9.00–25.47/ac). Maintenance of floods on ricefields until early March also benefits waterfowl and other waterbirds by providing foraging habitat throughout winter.

Key words agronomic benefits, habitat management, Mississippi Alluvial Valley, *Oryza sativa*, red rice, rice, straw disposal, wetlands, winter flooding, winter weeds

An alliance between rice agriculture and waterfowl management communities has existed for decades. Research has shown the importance of wetland complexes, including ricefields, in providing winter feeding and resting areas for North American waterfowl and other waterbirds (Delnicki and Reinecke 1986, Miller 1987, Elphick

and Oring 1998). Additionally, the hypothesis that winter habitat and feeding conditions contribute to waterfowl survival and recruitment generally has been accepted by scientists and the conservation community (Heitmeyer and Fredrickson 1981, Kaminski and Gluesing 1987, Dubovsky and Kaminski 1994). This connection with annual life-

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cycle events of waterfowl and other waterbirds underscores the importance of habitat provided by natural wetlands and flooded croplands during migration and winter.

Great potential to create winter habitat for waterfowl and other waterbirds exists in Mississippi Alluvial Valley (MAV) ricefields. Together, Arkansas (512,000 ha) and Mississippi (101,000 ha) produced more than half of the total United States rice harvest during our study (United States Department of Agriculture [USDA] National Agriculture Statistics Service 2002). However, only approximately 66,000 ha (11%) of harvested ricefields were flooded to provide winter habitat for waterfowl in these 2 states (Uihlein 2000). Fortunately, results from questionnaire surveys indicated that many MAV farmers were interested in managing habitat for waterfowl and did not believe winter flooding of cropland conflicted with other land management practices (Zekor and Kaminski 1987, Bray 1998). Moreover, private-lands programs initiated by public and private conservation organizations in the MAV have achieved considerable success in restoring wetlands and enhancing rice-lands through incentive and technical assistance programs (Payne and Wentz 1992, Baxter et al. 1996).

Although waterfowl clearly benefit from flooding of ricefields, effects of winter flooding on agricultural operations are less understood. Recent increases in rice acreage and yields in the MAV could motivate more landowners to participate in waterfowl management if agronomic benefits result from management practices. Winter flooding has potential to reduce costs of rice and soybean production by decreasing problems associated with managing residual rice straw, winter weeds, and red rice (*Oryza sativa* var.) (Emory 1994, Muzzi 1994). Residual rice straw is undesirable because it inhibits tillage and seedbed preparation. Furthermore, microbial decomposition of residual straw in spring competes with growing rice and soybeans for available nitrogen (Williams et al. 1972, Bacon 1991). Winter weeds, such as annual blue grass (*Poa annua*) and marsh buttercup (*Ranunculus sardous*), also inhibit seedbed preparation, compete with emerging crops, and must be eliminated by tillage or herbicide treatments. Lastly, competition from an aggressive weed known as red rice reduces yield and milling quality of commercial rice and has become increasingly problematic in the southern United States. Even with con-

temporary weed management strategies, reductions of rice yield and quality in the MAV cost growers \geq \$39 million annually (Bridges and Anderson 1992).

Consensus exists among rice growers and wildlife managers that defining and evaluating agronomic benefits of winter ricefield management is the best way to motivate increased landowner participation. Our objective was to test whether combinations of postharvest disking, winter flooding, and flood duration affected overwinter reductions of residual rice straw, spring biomass of winter weeds, and viability of red rice seed. We also compared costs of selected treatment combinations to recommend management practices that provided the greatest agronomic benefits.

Study area

We conducted replicated field experiments in winters 1995–1996 and 1996–1997 in the MAV of Mississippi. We selected 12 sites (6 sites \times 2 winters) in Bolivar (4 sites), Leflore (2), Sunflower (2), and Washington (4) counties (center of study area latitude 33° 26' 55.46", longitude -90° 38' 41.55"), where 65% of Mississippi's rice crop was harvested during our study (Mississippi Department of Agriculture and Commerce 1994–1996). Within each site (or farm), we selected 6 ricefields to apply treatment combinations. We selected sites based on capabilities of fields to support treatments and rice growers' willingness to cooperate. Soils at study sites were level montmorillonitic clays, classified as Vertisols of the Sharkey (*Chromic Epiaquerts*) and Alligator (*Alic Dystraquerts*) series, and Alfisols of the Forestdale (*Typic Endoaqualfs*) series. At various times in the past, fields were landformed to facilitate irrigation and drainage. Additionally, each field was bordered by permanent levees containing flashboard riser drainpipes.

Methods

Experimental ricefield treatments

We prescribed 2 treatments on experimental ricefields: 1) postharvest treatment and 2) winter-water management. With respect to postharvest treatment, growers either left rice stubble standing following harvest in August–September or disked stubble into soils. Disks were passed over fields twice to a depth of about 10 cm. Hereafter, we refer to postharvest treatments as stubble or

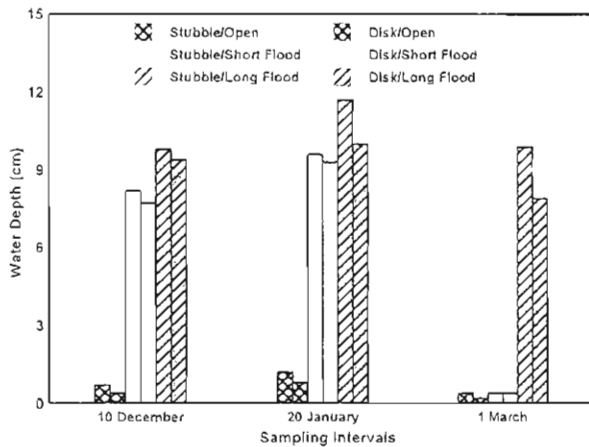


Figure 1. Mean water depths in experimental ricefields subjected to combinations of postharvest straw manipulation and winter-water management, Mississippi Alluvial Valley, Mississippi, winters 1995–1996 and 1996–1997. From beginning of winter (10 December), open fields were allowed to drain after rains; short flood fields were flooded until the waterfowl hunting season ended (20 January), then allowed to drain for remainder of winter; long flood fields were flooded until end of winter (1 March).

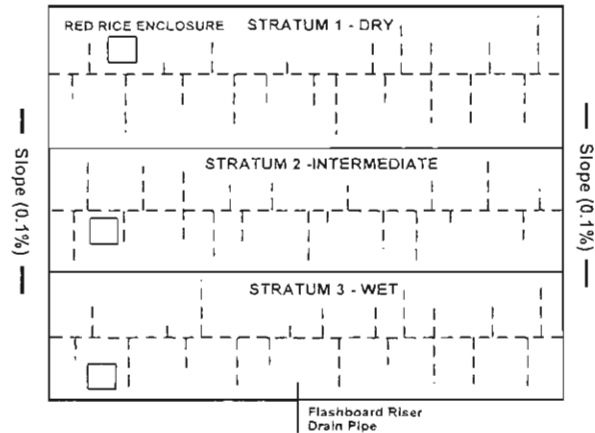


Figure 2. Stratum and transect design used to collect core samples along slope gradients of experimental ricefields in the Mississippi Alluvial Valley, Mississippi, winters 1995–1996 and 1996–1997. Core samples were collected at a rate of 1 per 0.75 ha, except for fields ≤ 12 ha, where a total of 15 samples was collected. Terminal points of vertical lines, extending above and below transect lines, represent randomly placed core sampling sites. Squares represent enclosures protecting samples of red rice (*Oryza sativa* var.) seed.

disked. Postharvest treatments were representative of management practices in Mississippi as aerial surveys classified most ricefields flooded in winter as standing (34%) and disked (50%) stubble (Uihlein 2000).

Following postharvest treatments, we prepared fields to support 3 levels of water management during winter: 1) open, where fields were left open to drain freely after rains; 2) short flood, where water control structures were closed by 1 November to impound rain and runoff, then opened on 20 January when the waterfowl hunting season ended; and 3) long flood, where water control structures were closed by 1 November and fields remained flooded until 1 March. Hereafter, we refer to levels of water management as open, short flood, and long flood (Figure 1). Once rainfall and runoff were sufficient to stabilize flooding, we maintained 65–70% water coverage on experimental ricefields.

Field methods

Stratification of experimental ricefields. Experimental ricefields had slope gradients of 0.05–0.30%, with highest elevations at the irrigation source and lowest at drainpipes. This gradient facilitated proper water management during the growing season. Because internal levees were removed after harvest, impounded rainfall formed a continuum of water depths that were greatest at

the lowest elevation. As rainfall accumulated, water gradually flooded areas of higher elevation, but the highest elevations seldom flooded. Fields left open during winter remained saturated at low elevations as runoff water gravitated toward drains. Because slope gradients affected water management and potentially experimental response variables, we divided fields into 3 equal-area strata and employed a stratified random design to collect samples within fields (Figure 2). We established transects through the center of each stratum, then used random distances along and perpendicular from transects to select sample locations.

Rice-straw and winter-weed sampling. To test effects of treatment combinations on biomass of rice straw and winter weeds, we collected samples at 3 time intervals during winter. The 3 intervals were evenly separated by 40 days and coincided with initial flooding (approximately 10 December), draining of short-flood treatments after the waterfowl hunting season (20 January), and draining of long-flood treatments before spring field preparation (1 March). We also collected a set of samples immediately after harvest but before disking (August–October), to establish a baseline for assessing subsequent reductions in straw biomass. We used a standard coring method (Murkin et al. 1994) to collect samples within fields. Samples generally were taken at a rate of 1 per 0.75 ha using a 10-cm-

diameter corer to a depth of 10 cm (volume = 785.4 cm³), although we took 15 samples in ricefields ≤ 12 ha. We extracted equal numbers of samples from each of the 3 strata within each ricefield. Samples of rice straw and winter weeds included entire plants (i.e., roots, stems, leaves) and were stored in plastic bags at -10°C until processed in the laboratory.

Red rice sampling. For red rice we assessed treatment effects on autumn-winter germination and overwinter seed decomposition (i.e., mass loss), the most likely mechanisms to affect seed viability in spring. To evaluate treatment effects on red rice, we used seeds of black-hulled red rice obtained from Mississippi State University Seed Technology Laboratory to prepare 0.35–0.75 g “mesh-bag” samples (10 seeds/bag) for placement in ricefields. We followed Nelms and Twedt (1996) on sample preparation and field methodology. We placed 2 sets of 3 red rice samples (total of 6) in each ricefield following completion of postharvest disking (15 October). We used one set to estimate proportions of seeds germinating in winter and remaining viable in spring; these samples were not dried or weighed before field placement. We used the second set to estimate overwinter decomposition, and these samples were dried to constant mass (± 0.5 mg) at 23°C. In both cases, we distributed the 3 samples across slope gradients within fields and protected them with wire enclosures (Figure 2). We secured samples on the soil surface in stubble fields and buried them 5–10 cm in disked fields. We retrieved samples at the end of the field season (1–10 March).

Laboratory methods

We washed core samples through #6 mesh (3.35 mm) and manually removed rice straw and winter weeds. We oven-dried resulting samples to a constant mass (± 0.5 mg) at 87°C. We transported red rice viability samples to the Mississippi Department of Agriculture and Commerce Seed Testing Laboratory, Mississippi State University. Following gentle washing to remove sediment, we used the presence of seed mesocotyl or coleoptile to assess winter germination (Miller 1983). We then placed samples in an outdoor greenhouse (approximately 15 March), where they remained saturated and exposed to ambient temperatures. We conducted 4 successive spring germination counts at 2-week intervals. At the end of 8 weeks (approximately 15 May), we checked seeds not germinated for dor-

mancy with a tetrazolium hydrochloride test (Delouche et al. 1962). We considered seeds viable if they germinated in the greenhouse or were live but dormant. We washed samples used to estimate red rice decomposition through #30 mesh (600 μ m) to remove sediment, then oven-dried to constant mass (± 0.5 mg) at 23°C.

Statistical analyses

We applied postharvest (i.e., stubble or disked) and water management treatments (i.e., open, short, or long flood) in combination to 1 ricefield at each of 6 sites in each of 2 winters (i.e., 72 experimental units = 2 postharvest treatments \times 3 water management treatments \times 6 sites \times 2 winters). Because rice often was grown in annual rotations with soybeans, we selected different sites each winter. Furthermore, because land-use histories, cultural practices, soils, and rainfall were more consistent within than among sites, sites served as experimental blocks.

Rice straw and winter weed data. We used samples from all strata to calculate mean biomass (kg/ha, dry mass) of rice straw and winter weeds for each ricefield and time interval. We analyzed resulting estimates using a mixed-model analysis of variance (ANOVA) in a randomized complete block design with repeated measures (SAS 1994, Littell et al. 1996). Treatment combination, sampling interval, and winter were fixed effects. We considered sites (i.e., blocks) as random effects, and because they changed annually, sites were nested in winters. When significant fixed effects were detected ($P \leq 0.05$), we made all pairwise comparisons of differences in least squares means (SAS 1994, Littell et al. 1996).

Red rice data. We used the first set of prepared red rice samples (3 subsamples \times 10 seeds/subsample = 30 seeds) to calculate percentages of seeds germinating in winter and remaining viable in spring. We used the second set of samples to calculate decomposition of red rice, measured as percent dry biomass remaining in spring. Analyses were similar to those for rice straw and winter weeds, except there were no repeated measures. That is, we tested effects of treatments on percentages of red rice viable in spring, germinating in winter, and biomass in spring, with a mixed-model ANOVA in a randomized complete block design. Treatment combinations and winter were fixed effects, and sites (i.e., blocks) were considered random effects and nested in winters. When signifi-

Table 1. Least squares means^a for biomass (kg/ha dry mass) of rice straw and winter weeds^b in experimental ricefields subjected to combinations of postharvest straw manipulation and winter-water management^c, Mississippi Alluvial Valley, Mississippi, winters 1995–1996 and 1996–1997.

	Stubble																		Disk																		P																		
	Open									Short flood									Long flood									Open										Short flood									Long flood								
	\bar{x}	SE	n	\bar{x}	SE	n	\bar{x}	SE	n	\bar{x}	SE	n	\bar{x}	SE	n	\bar{x}	SE	n	\bar{x}	SE	n	\bar{x}	SE	n	\bar{x}	SE	n	\bar{x}	SE	n	\bar{x}	SE	n																						
Rice straw	6,079	AB	506	12	6,746	A	522	11	5,762	AB	506	12	5,113	BC	506	12	4,409	CD	506	12	3,847	D	530	10	<0.01																														
Winter weeds	48.1	A	9.6	12	26.9	AB	10.0	11	13.9	B	9.6	12	40.4	A	9.6	12	11.2	B	9.6	12	5.58		10.3	10	0.01																														

^a Means within rows with unlike letters differ ($P \leq 0.05$).

^b Common winter weeds included *Cerastium glomeratum*, *Lepidium virginicum*, *Myosurus minimus*, *Poa annua*, *Ranunculus sardous*, *Rumex crispus*, *Senecio glabellus*, *Sibara virginica*, and *Veronica peregrina*.

^c Open: fields allowed to drain after winter rains. Short flood: fields flooded until the waterfowl hunting season ended (20 January), then allowed to drain for remainder of winter. Long flood: fields flooded until 1 March.

cant fixed effects were detected ($P \leq 0.05$), we made all pairwise comparisons of differences in least squares means.

Relative costs of management practices

We calculated relative costs of different treatment combinations using data in Mississippi Rice and Soybean 2002 Planning Budgets (Spurlock and Laughlin 1992, Mississippi Cooperative Extension Service 2001a, b). Planning Budgets provided data tables comprising average costs for various farm operations and were derived from annual surveys of rice and soybean producers in the MAV.

Results

Precipitation totaled 12.1 and 29.5 cm during the harvest period of 1 August to 30 October in 1995 and 1996; these values bracketed the 30-year average of 22.3 cm (National Oceanic and Atmospheric Administration 1992). Precipitation totaled 36.9 and 72.5 cm from 1 November to 10 March in 1995–1996 and 1996–1997; these values also bracketed the 30-year average of 52.0 cm. Average daily temperature was 7.6° C between 1 November and 10 March 1995–96 and 8.8° C during this period in 1996–1997; the 30-year average was 7.9° C. Therefore, the autumn and winter of 1995–1996 was relatively dry with near-average temperatures, whereas winter 1996–1997 was relatively wet with above-average temperatures.

Experimental ricefields ($n=72$) encompassed a 2-winter total of 1,275 ha and averaged 18.5 ha/field (range 4.5–46.1 ha). We collected and processed 6,386 core samples to estimate biomass

of residual rice straw and winter weeds during the experiment. We were not able to manage water effectively on 1 stubble-short flood (1995–1996) and 1 disked-long flood treatment combination (1996–1997); thus, we eliminated these 2 fields from analyses. Also, rodents entered wire enclosures and damaged several red rice samples, rendering them unusable. Thus, we used 63 experimental ricefields to analyze data on spring viability and winter germination of red rice and used 62 ricefields to assess decomposition of red rice.

Rice straw and winter weeds

Rice straw. Straw biomass varied among treat-

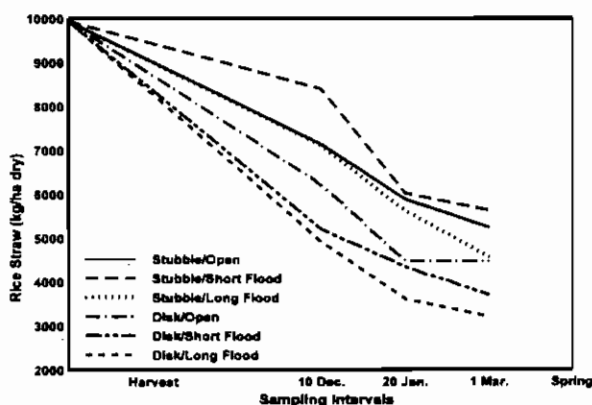


Figure 3. Decreases in biomass (kg/ha dry mass) of residual rice straw in fields subjected to combinations of postharvest straw treatment and winter-water management, Mississippi Alluvial Valley, Mississippi, winters 1995–1996 and 1996–1997. From beginning of winter (10 December), open fields were allowed to drain after rains; short flood fields were flooded until the waterfowl hunting season ended (20 January), then allowed to drain for remainder of winter; long flood fields were flooded until end of winter (1 March).

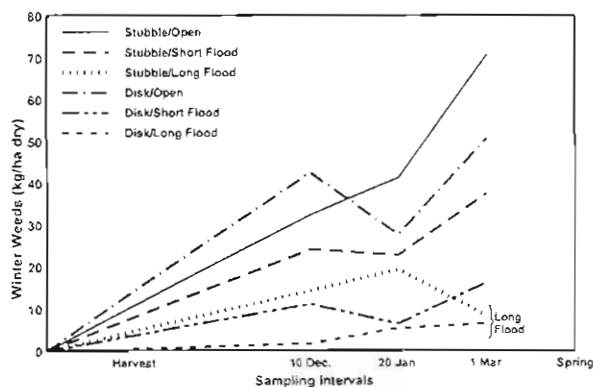


Figure 4. Increases in biomass (kg/ha dry mass) of winter weeds in ricefields subjected to combinations of postharvest straw treatment and winter-water management, Mississippi Alluvial Valley, Mississippi, winters 1995-1996 and 1996-1997. From beginning of winter (10 December), open fields were allowed to drain after rains; short flood fields were flooded until the waterfowl hunting season ended (20 January), then allowed to drain for remainder of winter; long flood fields were flooded until end of winter (1 March).

ment combinations ($F_{5, 48} = 7.63$, $P < 0.01$), with a general trend of reduction promoted by disking and flooding (Table 1). Straw biomass also varied among intervals ($F_{2, 114} = 43.17$, $P \leq 0.01$) and, when averaged over treatments, decreased 35% between harvest and 10 December, then decreased an additional 10% by 20 January and another 10% by 1 March. Straw biomass was reduced most throughout winter by the disk-long flood combination (Table 1), resulting in a final 68% reduction from 9,938 kg/ha after harvest to 3,209 kg/ha in spring (Figure 3). Straw biomass was reduced least by the stubble-short flood combination (43%), from 9,938 kg/ha to 5,624 kg/ha in spring (Figure 3). Straw biomass was reduced similarly in the stubble-long flood and disk-open combinations (53-54%; Figure 3), and this similarity is important regarding later comparisons of management practice costs. There was no effect due to winter ($F_{1, 10} = 0.00$, $P = 0.95$), or significant interactions between winter and treatment ($F_{5, 48} = 0.93$, $P = 0.47$), winter and interval ($F_{2, 114} = 2.42$, $P = 0.09$), treatment and interval ($F_{10, 114} = 0.77$, $P = 0.65$), or winter, treatment, and interval ($F_{10, 114} = 0.57$, $P = 0.84$).

Winter weeds. Biomass of winter weeds also varied among treatment combinations ($F_{5, 48} = 3.77$, $P = 0.01$), with a general trend of suppression promoted by flooding, and to a lesser extent disking (Table 1). Biomass in some treatment combinations decreased as temperatures cooled in mid-winter

(Figure 4; 20 January), and increased as temperatures warmed in spring (1 March), but variation among time periods was marginal ($F_{2, 114} = 2.22$, $P = 0.11$). Both postharvest conditions combined with long floods suppressed weed growth throughout winter, averaging ≤ 8 kg/ha by spring (Figure 4). In contrast, biomass of weeds was greatest in open fields throughout winter, ranging 50-70 kg/ha by spring (Figure 4). There was no effect due to winter ($F_{1, 10} = 1.44$, $P = 0.26$), or interactions between winter and treatment ($F_{5, 48} = 0.57$, $P = 0.72$), winter and sampling interval ($F_{2, 114} = 1.14$, $P = 0.32$), treatment and interval ($F_{10, 114} = 0.82$, $P = 0.61$), or winter, treatment, and interval ($F_{10, 114} = 0.83$, $P = 0.60$).

Viability of red rice

Treatment combination interacted with winter to effect viability of red rice seed in spring ($F_{5, 41} = 3.02$, $P = 0.02$). Also, treatment combination interacted with winter to effect biomass remaining in spring ($F_{5, 40} = 5.22$, $P < 0.01$). Therefore, we analyzed all data on red rice seed within winters.

Spring viability. Red rice seeds from our sampling stocks were $\geq 85\%$ viable before preparation and placement in fields. This rate of viability was similar to previous studies (e.g., McGinn and Glasgow 1963, Powers et al. 1978), and control samples stored over winter maintained $\geq 85\%$ viability. During spring viability tests, greenhouse temperatures from 15 March until 15 May ranged from 10-20°C in both years. Among viable seeds recovered from field samples, 93% sprouted in the greenhouse and 7% remained live but dormant.

Treatment combinations had no effect on viability of red rice seed in spring 1996 ($F_{5, 19} = 1.28$, $P = 0.31$), and marginally affected viability in spring



Ricefields are important foraging habitat for waterfowl and other waterbirds in several North American wintering areas, including the Mississippi Alluvial Valley.

1997 ($F_{5, 22}=2.30, P=0.08$). Viability of red rice in spring 1997 was reduced to an average 8.8%, when seed was left on the soil surface amid standing stubble (Table 2). This was the only winter and suite of treatment combinations that reduced viability $\leq 20\%$.

Winter germination. Treatment combinations had no effect on germination of red rice seed in winter 1995–1996 ($F_{5, 19}=1.29, P=0.31$). In contrast, treatments affected germination in winter 1996–1997 ($F_{5, 22}=3.33, P=0.02$), when germination tended to increase in fields left in stubble and open to drain (Table 2). Among all treatments and winters, only the stubble-open combination in 1996–97 was effective in germination of $\geq 83\%$. Germination in other combinations and winters was $\leq 62\%$.

Biomass. Treatment combinations affected red rice biomass left in spring 1996 ($F_{5, 19}=3.34, P=0.02$), and spring 1997 ($F_{5, 21}=4.99, P<0.01$), although trends were opposite between winters (Table 2). In general, long floods reduced biomass by spring 1996, whereas leaving fields open did by spring 1997. Nonetheless, biomass remaining in all treatment combinations was $\geq 80\%$ by spring 1996, and $\geq 55\%$ by spring 1997.

Discussion

Reduction of rice straw

Rice growers benefit from rapid decomposition of rice straw after harvest by saving time and money in subsequent agriculture operations. An array of biological and physical forces act on the nearly 10,000 kg/ha of rice straw present after harvest. As decomposition begins a continuum of organic carbon compounds forms among the rice straw, soil microbes, and soil organic matter. Rice straw is relatively resistant to decomposition because it contains a high ratio of carbon to nitrogen (i.e., C:N ratio; Norman et al. 1990, Eagle et al. 2001) and $\geq 10\%$ silica (Marschner 1995).

Incorporation of crop residues by disking generally increases microbial decomposition by increasing contact between straw and soil microbes (Molina et al. 1985, Brady and Weil 1996). Straw biomass in disked fields averaged 28% less than fields with

Table 2. Least-squares means^a for variables measuring responses of red rice (*Oryza sativa* var.) seeds placed in experimental ricefields subjected to combinations of postharvest straw treatment and winter-water management^b, Mississippi Alluvial Valley, Mississippi, winters 1995–1996 and 1996–1997.

Response variable (%)	Stubble						Disk					
	Open			Long flood			Open			Short flood		
	\bar{x}	SE	n	\bar{x}	SE	n	\bar{x}	SE	n	\bar{x}	SE	n
1995–1996												
Viability in spring	27.8	7.4	6	48.9	10.5	3	25.0	7.4	6	20.0	8.1	5
Winter												
germination	57.2	7.2	6	55.2	9.9	3	40.0	7.2	6	40.8	7.8	5
Biomass in spring	86.3AB	2.2	6	92.0A	3.1	3	79.4C	2.4	5	84.9ABC	2.4	5
1996–1997												
Viability in spring	5.3	9.9	5	7.8	9.2	6	13.3	9.2	6	27.2	9.2	6
Winter												
germination	83.1A	12.6	5	61.1AB	12.0	6	62.2AB	12.0	6	48.4BC	12.0	6
Biomass in spring	55.0A	5.2	5	63.3AB	5.2	5	62.8AB	5.0	6	73.6C	5.0	6

^a Means within rows with unlike letters differ ($P \leq 0.05$).

^b Open: fields allowed to drain after winter rains. Short flood: fields flooded until the waterfowl hunting season ended (20 January), then allowed to drain for remainder of winter. Long flood: fields flooded until 1 March.



We used standard core sampling techniques to estimate biomass of residual rice straw and winter weeds.

untreated stubble. However, decreased biomass in disked fields may have been due to straw dispersal as well as increased decomposition. We noted that in fields where disking separated straw and roots from soil, flooding interacted with winds to disperse and sometimes export straw from fields. The effect likely was greatest in disk-long flood treatment but occurred to some extent in all disk treatments because of occasional heavy rains.

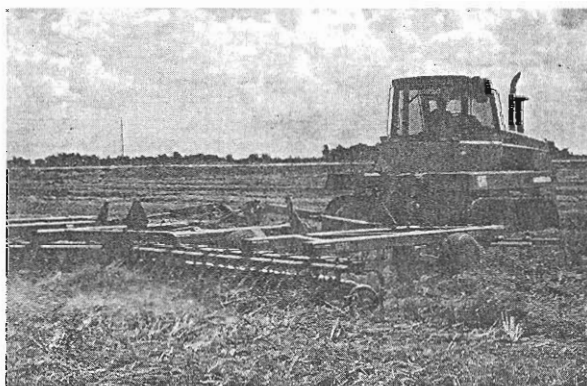
In theory, anaerobic conditions develop in flooded soils and reduce microbial decomposition of plant residues (Bernard and Gorham 1978, Brinson et al. 1981). Generally, decomposition is greatest when soils alternate between wet and dry conditions (Birch 1958, VanShreven 1967, Sorenson 1974). Therefore, fields flooded throughout winter should have decreased decomposition and increased straw biomass. However, our results indicated that less straw remained when fields were flooded until early March (long flood). Similarly, straw biomass decreased when ricefields were flooded in winter in California (Bird et al. 2000). Perhaps water management during winter resulted in sufficient periods of soil exposure, caused by wind and evaporation, to maintain aerobic conditions. Alternatively, a succession of aerobic and anaerobic microbes may have decomposed rice straw as demonstrated in California (Bossio and Scow 1995, 1998), or flood waters may have buffered extreme temperatures and facilitated microbial activity (Brinson et al. 1981, Bossio and Scow 1995). In any case, winter flooding has increased rather than decreased rice straw decomposition in major rice-producing regions of the United States that are important as wintering areas for waterfowl.

Other biological processes also facilitate straw decomposition during winter. Bird et al. (2000) demonstrated that foraging by captive waterfowl increased straw decomposition in experimental plots in California, and Van Groenigen et al. (2003) reported similar trends for a large-scale field experiment. We did not assess waterfowl use of experimental fields, but use occurred, and was a factor in disturbing rice straw. Flooding encourages use by waterfowl that physically mix straw, roots, and soil, and increases populations of aquatic invertebrates (Manley et al. 2004) that facilitate decomposition by shredding and consuming organic detritus.

Growth of winter weeds

Because most seeds do not germinate when covered by water, flooding of commercial rice in the growing season is as much for weed control as for irrigation (Miller 1983, Miller and Houston 1986, Helms 1996). Similarly, winter weeds, such as bluegrass and buttercup can be suppressed by flooding fields after harvest. Winter flooding decreases available oxygen and prevents increases in temperatures from stimulating germination and growth of winter weeds.

Tillage (e.g., disk, plow, harrow) historically has been used to control weeds in croplands (Molina et al. 1985). Biomass of weeds in our disked ricefields averaged 36% less than in fields left untreated, but flooding was more effective in controlling winter weeds. Although the effect of long and short floods did not differ, only combinations involving long floods reduced spring biomass of weeds below 10 kg/ha (Figure 4). Control of winter weeds may be the most important agronomic benefit of winter flooding, particularly if flooding can be integrated



Fall disking followed by flooding until early March was most effective in reducing residual rice straw and suppressing winter weeds, but this practice incurs additional costs.

with minimum and no-till crop production systems to increase net economic returns (e.g., Anders et al. 2006).

Viability of red rice

Red rice is a major challenge for MAV rice growers. Red rice reduces yields of commercial rice by competing for limited space, light, and nutrients (Diarra et al. 1985, Dunand 1988, Pantone et al. 1992). Also, red rice seeds disperse prior to and during harvest, exhibit prolonged dormancy, and maintain vigor (Eastin 1978). Herbicides that selectively control red rice in growing rice crops are in early stages of development. Some producers believe that enhancing decomposition of red rice seed is the best control strategy, whereas others contend increasing premature germination in autumn and winter is more effective. Choice of a best strategy may be further complicated by environmental conditions.

Viability of red rice responded differently to treatments in winters 1995-1996 and 1996-1997. Viability of red rice in spring 1996 was $\geq 20.0\%$, and there was little evidence of treatment effects. In contrast, viability of red rice in untreated stubble averaged 8.8% in spring 1997 and was as low as 5.3% in stubble-open fields. We believe the difference in response between winters resulted from weather patterns; increased temperatures and precipitation in winter 1996-1997 promoted premature germination of seeds. Nevertheless, our results were inconsistent and red rice will continue to challenge growers in the MAV to design integrated control strategies involving crop rotation, cultural practices, and herbicides.

Economic implications

Effects of experimental treatments on response variables can influence management practices of MAV rice growers by altering production costs. To assess economic implications of alternative management strategies, we first compared costs of the disked-open and stubble-long flood treatment combinations, which provided equivalent levels of straw decomposition. In doing this, we assumed winter flooding would eliminate the need for 2 passes of a disk in autumn at a savings of \$34.22/ha (U.S.) (\$13.85/ac). However, some cooperating rice growers may elect to perform 1 additional pass in spring with a disk-harrow in stubble fields that were flooded until early March (total of 2 in spring). Adding 1 spring tillage operation reduced

potential savings to \$25.05/ha (\$10.14/ac) if the next crop was rice and \$22.24/ha (\$9.00/ac) if the next crop was soybeans. Maximum reduction of rice straw (68%) required disking and flooding until early March, but autumn disking incurred costs. In contrast, costs of winter flooding generally are negligible in leveled ricefields, where growers only need to close water control structures to impound winter rains. However, winter flooding can increase management costs by \$3.76/ha (\$1.52/ac) if temporary irrigation levees within fields must be repaired for effective water management.

Biomass of weeds in stubble and disked ricefields flooded until early March was ≤ 10 kg/ha in spring. If one less pass of a disk-harrow is needed when weed biomass is ≤ 10 kg/ha, growers would save an average \$11.66/ha (\$4.72/ac) in production costs for rice and \$13.20/ha (\$5.34/ac) for soybeans. If an aerial application of herbicide can be omitted during spring field preparation because flooding suppressed winter weeds, a cost savings of \$28.71/ha (\$11.62/ac) would accrue. Thus, control of winter weeds represents the best opportunity for MAV growers to decrease production costs. Absence of weeds in spring persuaded several rice growers cooperating in our experiment to forego expensive aerial applications of "burn-down" herbicides.

Management implications

Combining postharvest straw treatment with winter-water management provides alternatives to address agronomic challenges facing rice and soybean producers in the MAV. The combination of disking and flooding until early March reduced straw biomass 68%, from 9,938 kg/ha after harvest to 3,209 kg/ha in spring. Flooding until early March, with or without disking, was most effective in suppressing winter weeds and reduced spring biomass 83% compared to the average of other water management regimes (Figure 4). To achieve maximum decomposition of rice straw and suppression of winter weeds, we recommend autumn disking followed by flooding until early March. However, growers should consider that long floods alone (stubble-long flood) reduced rice straw from 9,938 kg/ha after harvest to 4,610 kg/ha in spring, and the long-flood alone was effective in suppressing winter weeds (Figure 3). Therefore, to achieve maximum agronomic benefits we recommend rice growers forgo autumn disking and flood until early

March to obtain moderate straw reduction, effective weed suppression, and a potential net savings of \$22.24–62.93/ha (\$9.00–25.47/ac). If autumn disking is deemed necessary, we suggest a light application to conserve costs, soils, water quality, and waterbird habitat (Manley 1999).

In summary, winter flooding of ricefields has potential to help MAV rice growers with straw and weed management while providing habitat for migrating and wintering waterbirds. Although winter flooding can reduce management costs, environmental benefits such as soil and nutrient retention, increased quality of runoff waters, and wildlife habitat may be as important as economic returns in future negotiation of regulatory and other public policies. We recommend winter flooding as an integrated conservation tool and best management practice that benefits MAV growers, the environment, and wetland-dependent wildlife.

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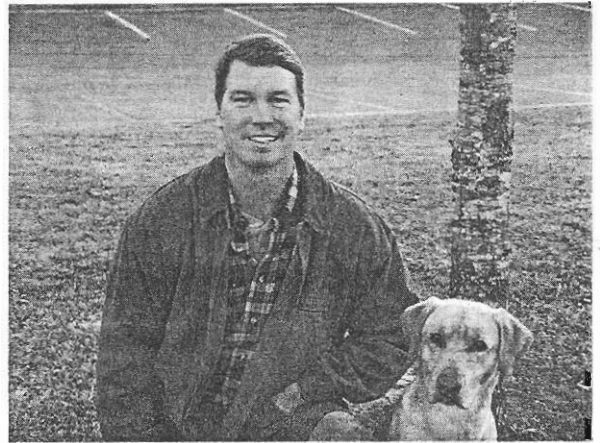
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